

Development of ground motion relations for seismic hazard analysis in Puerto Rico
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Non-technical Summary: This project develops regional ground-motion relations, describing the amplitude and frequency content of motions as functions of magnitude and distance. These relations have direct bearing on seismic design. We also perform work on improving magnitude estimates in regional seismicity catalogs, which are the basic building blocks of probabilistic seismic hazard analysis.

Introduction

Puerto Rico lies on the boundary between the North American and the Caribbean plates. It is surrounded and crossed by active seismic faults and is a focus of brisk seismic activity. The island has a significant seismic hazard, as evidenced by the hundreds of moderate (M 4 to 5) events recorded in the last two and a half decades. About 10,000 earthquakes have been located since the inception of the Puerto Rico Seismic Network in 1974. Since Spanish settlement in the early 1500's, there have been at least four destructive earthquakes, with intensities greater than VII on the Modified Mercalli Intensity Scale, causing loss of life and substantial property damage. Two major ($M > 7$) events occurred in this century (1918 and 1943). Historical data show that Puerto Rico has been subjected to a strong earthquake about every 75 years. A possible great earthquake in 1787 (M 8 to 8.2) appears to have occurred along the main seismic zone near the Puerto Rico trench to the north of the island (McCann, 1985). The seismic environment is complex, with both crustal and subduction events contributing to the hazard.

Despite its high seismic risk, Puerto Rico lags behind other seismically-active regions of the United States in terms of research to adequately assess and mitigate earthquake hazard. Of particular importance is the development of ground-motion relations, to estimate peak motions and response spectra as functions of magnitude and distance. These relations are a cornerstone of seismic hazard analysis: their development has been completed under the current project. We also develop and calibrate a moment-magnitude based magnitude measure that can be applied to Puerto Rico network data. This will substantially improve the catalog available for seismic hazard analyses.

Progress to Date

We have used records from regional short-period and broadband seismographic stations to compile a ground motion database for the development of ground motion relations (data may be obtained by email request to dariush@ccs.carleton.ca). The useable ground-motion data are insufficient to determine ground-motion relations directly by empirical regression (eg. as per California), but can be used to determine input parameters for the development of stochastic ground-motion relations, and to validate the developed relations (eg. as per eastern North America).

The stochastic method has been one of the most useful tools in ground-motion modeling over the past 15 years (Boore, 1983; McGuire et al., 1984; Boore and Atkinson, 1987; Atkinson and Boore, 1995; Toro *et al.*, 1997; Atkinson and Silva, 2000). While the first applications of the method dealt with modeling events as point sources (Boore, 1983; Boore and Atkinson, 1987), the model has been lately generalized to the case of finite propagating ruptures (Schneider *et al.*, 1993; Beresnev and Atkinson, 1997, 1998b, 1999; Atkinson and Silva, 2000). Our approach to the development of ground motion relations for Puerto Rico is similar in concept to that used by Atkinson and Boore (1995) for eastern North America and Atkinson and Silva (2000) for California. These studies used a stochastic simulation approach, with the model parameters calibrated against the recordings of regional ground motion data. In this study, our model parameters are determined from our analysis of the calibrated subset of seismographic data from the Puerto Rico seismic network. We use the finite-fault stochastic model, as opposed to a point-source model.

Stochastic finite-fault modeling is a valuable tool for interpreting the observed ground motion data, particularly since region-specific attenuation parameters can be readily incorporated. The essence of the method is that a specified fault plane (specified by length, width, orientation in space) is subdivided into a 2D array of subfaults, each of which is small enough to be treated as a point source. The rupture initiates at a specified subfault, and propagates across the fault plane with a specified rupture velocity. The seismic radiation from each of the subfaults is modeled using the stochastic point-source model. The ground motion at a specified site is obtained by summing the contributions from all of the subfaults, lagged in time according to the time of rupture initiation on the subfault and the site-source geometry. The stochastic finite-fault method has been shown to provide accurate ground motion predictions on average for events of moderate-to-large magnitude, over a wide frequency range (0.2 to 30 Hz), and in a variety of tectonic settings (eg. Schneider et al., 1993; Atkinson and Silva, 2000; Beresnev and Atkinson, 1997, 1998a,b; 1999, 2001). The accuracy of the finite-fault simulation method is comparable to that of deterministic methods based on more detailed modeling of wave generation and propagation (eg. Somerville et al., 1991), as was demonstrated for the 1985 Michoacan, Mexico earthquake of **M** 8 (Beresnev and Atkinson, 1997) and other events (Hartzell et al., 1999).

The strength of the stochastic method is that it combines a basic theoretical understanding of earthquake generation and propagation processes with empirical information that can be obtained from recordings of small-to-moderate events. To develop stochastic ground-motion relations, a model of regional attenuation is required; we need to know the geometric spreading and the frequency-dependent Quality factor, Q . It is generally accepted that geometric spreading can be modeled as R^{-1} amplitude decay within the distance range dominated by direct waves: generally within 50 to 100 km. At regional distances, there is a transition to surface-wave attenuation, with geometric spreading of $R^{-1/2}$. The anelastic attenuation model can be determined empirically from the calibrated regional ground-motion data. We use data beyond 100km, for which $R^{-1/2}$ geometric spreading is assumed. (Note: this assumption is verified by checking the attenuation slope at low-to-intermediate frequencies; the observed attenuation is indeed significantly less than R^{-1}). We have determined that, for Puerto Rico, Q appears to be very similar for both the deep (>30 km) and shallow (<30 km) event paths, and is intermediate to ENA and California Q values. We therefore use a single Q model to represent events at all

depths. This Q model, given by $Q = 355 f^{0.59}$, is an important input to the regional ground-motion relations.

Finite-fault stochastic simulations, using a modified version of the method of Beresnev and Atkinson (1998a, 1999, 2001), are used to develop a simulated ground-motion database for earthquakes of moment magnitude 4 to 7.5 over a broad range of distances. The method contains a generic finite-fault source model, with region-specific attenuation parameters. This method has been shown to accurately reproduce ground-motion amplitudes in a wide variety of tectonic settings, including both eastern and western North America (Beresnev and Atkinson, 2001). The simulated database was regressed to develop regional ground-motion relations. Table 1 provides the fitted equations for the ground motion relations for Puerto Rico (horizontal component). These relations were submitted for publication in a special issue of *Tectonophysics*, in January 2002.

We compare the ground motion relations for Puerto Rico with the ground motion relationships for other regions. The other regions are Eastern North America (Atkinson and Boore, 1995), California (Atkinson and Silva, 2000) and empirical global relations for subduction zones (Atkinson and Boore, 2002). In each case, we selected ground motion relations that can be referenced to a specific model. The ENA relations of Atkinson and Boore (1995) are based on a stochastic point source model with a two-corner source spectrum to mimic finite fault effects. The California relations are based on a two-corner stochastic source model calibrated against the California strong motion database. The global subduction relations of Atkinson and Boore (2002) are strictly empirical, based on regression analysis of thousands of records; separate regressions were performed for in-slab and interface events.

Figure 1 shows the regional comparison at 1Hz frequency for magnitude **M7.0**. The Puerto Rico ground motions are broadly comparable to stochastic ground motion relations obtained for North America (where the California and ENA relations are similar). Differences are attributable to regional variations in ground motion propagation parameters. There are three main parameters that control the behavior of PSA (pseudo-acceleration) and which may vary regionally. The first one is the crustal and near-surface amplification. Another parameter that controls the behavior of PSA, especially at large distances, is the regional Q-value. At large distances Puerto Rico ground motion curves lie between those of ENA and California, since the Puerto Rico Q-value is intermediate to those for ENA and California. The third parameter that makes the PSA in Puerto Rico relations deviate from the other relations for North America is differences in the hinge points of the attenuation curve, reflecting regional differences in crustal structure. The ground motion relations for bedrock for ENA have been multiplied by generic factors (Adams et al., 1999) to convert them to a “firm ground” (NEHRP C) site condition. NEHRP site classification is based on the shear wave velocity (see Borchardt, 1995): NEHRP A=($v_s > 1500$ m/s), B=(760-1,500 m/s), C=(360-760 m/s), D=(180-360 m/s) and E=(< 180 m/s). The generic soft rock site condition (NEHRP C) applies for the California relations (“rock” relations of Atkinson and Silva, 2000) and is provided for the global subduction zones (Atkinson and Boore, 2002). The Puerto Rico curves represent soft rock (NEHRP C). The plotted curves are thus roughly comparable with the attenuation relations of the other regions in terms of site conditions.

We are also working on development of a moment-magnitude-based catalog for Puerto Rico. Such a catalog would be a valuable tool, as the seismicity catalog is the most basic building block of a probabilistic seismic hazard analysis. In Puerto Rico, there has been a long-standing problem with regional magnitude determinations and their apparent lack of consistency with global scales such as m_b . What is really needed for hazard analysis is a moment-magnitude-based catalog. We will work on developing such a catalog from the PRSN waveform data that we have compiled. Because of the calibration problems and clipping problems for so much of the data, the scale will utilize the coda approach, with calibration of the scale against the more limited data that have known absolute amplitude levels. The basic idea is as follows.

It is well known that the conspicuous coda observed on short-period regional seismograms is produced from the scattering of body waves by heterogeneities distributed throughout the lithosphere, as proposed by Aki and Chouet (1975), in addition to a multitude of other effects such as site response. The coda waves are usually defined as the waves arriving after twice the travel times of primary S waves (Rautian and Khalturin, 1978), which is well beyond the strong part of the S-wave signal, and thus beyond the signal segment that most often clips. Many studies have exploited the desirable features of the coda in a variety of source and attenuation studies. In particular, coda studies are attractive because the rate (slope) of the coda amplitude decay curve as a function of lapse time (time measured from the origin time) is independent of source-receiver distance (eg. Biswas and Aki, 1984).

The stability of coda, with respect to path, has been well documented at local distances. The stability, or uniform coda shape, is consistent with the model of coda as the superposition of waves backscattered from random heterogeneities in the earth's crust and upper mantle (Aki, 1969). The coda stability allows the isolation of relative, radiation-pattern averaged source effects apart from site and path effects. Aki (1980) proposed the use of coda amplitudes, rather than duration, to obtain higher precision magnitude estimates. A generalized form of the Biswas and Aki (1984) formula is

$$\text{Log}_{10} (A(f, t)) = c - a \log_{10} (t) - b(f)t$$

where A is the amplitude of coda as a function of time, c is the source term and b is related to the Q factor by the $b = (\log_{10} e) \pi f / Q$.

Our research has focused on finding values of c , a and b appropriate for the PRSN and IRIS stations. The amplitude decay rate and the duration of the coda are indicative of the size of the earthquake. We are calibrating coda amplitude moment measurements using the coda amplitudes of those events for which seismic moments had been determined by correlating these coda parameters with moment magnitude for the subset of data with known amplitude calibration. This correlation will then be applied to the remainder of the uncalibrated data, to develop a moment-magnitude catalog for the PRSN data from 1991 through 2001.

The technique is effective because once the relationship between coda parameters and moment-magnitude is established, the scale can be applied to other past events of unknown calibration, even if the strongest part of the signal is clipped. This works because it is only the decay rate and duration of the coda that is being used. Since coda waves are known to be

influenced less by path and radiation effects than are direct waves, especially for local earthquakes. Thus, coda potentially provides high precision estimates of source size such as magnitude and moment, with less path bias than direct waves.

The initial efforts on this part of project have involved using earthquake data from the region to determine the appropriate modifications to the Biswas and Aki (1984) formula. A dataset of regional earthquakes has been selected to determine the constants a , b and c for the PRSN and IRIS seismic stations. We hope to confirm the stability of coda in this region, or, if not, to work out ways to correct the results so that reliable magnitude estimates can be obtained. To do this, we have processed all records from these stations, and obtained coda decay curves. Calculation of residuals, allowing identification of trends that remain after subtracting the estimated source size, is the technique we are using to examine other possible effects on the coda.

For all records we first deconvolve the time series to velocity, then apply an 8th order, zero-phase (four poles, two passes) Butterworth filter for a few narrow frequency bands ranging between 0.1 and 8.0 Hz. For each component the narrowband envelope at center frequency f is calculated. A noise correction makes virtually no difference for larger events with long codas with good signal-to-noise ratio. However for small events with short codas the noise could have a larger relative effect on the amplitude. To overcome this problem we apply signal-to-noise tests to ensure that our late coda measurements were at least a factor of 2 larger than the pre-event noise. We then take the log of the envelopes, average the two horizontal envelopes, and apply smoothing. It is preferable to use the horizontal components since S -waves have better signal-to-noise ratio, and averaging the two provides a smoother envelope than a single component alone. We note that this processing could also be done on a single vertical component.

The work on the calculation of moment magnitude based on these analyses of the coda will be complete at the end of this project year.

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Table 1. Ground Motion Relations for Puerto Rico (Horizontal Component)

$$\log PSA(f, R) = c_1 + c_2(M-6) + c_3(M-6)^2 + hingeFunction + c_4R$$

$$R = (D^2 + \Delta^2)^{0.5}$$

$$\Delta = -7.333 + 2.333 M$$

$$hingeFunction = (-1.88 + 0.14 M) \log(R)$$

for $R \leq 75$ km

$$hingeFunction = (-1.88 + 0.14 M) \log(75)$$

for $75 \text{ km} \leq R \leq 100 \text{ km}$

$$hingeFunction = (-1.88 + 0.14 M) \log(75) - 0.5 \log(R/100)$$

for $R \geq 100 \text{ km}$

PSA is 5% damped horizontal component pseudo-acceleration in cm/sec^2 ; f in hertz; M , Moment magnitude; D = closest distance to fault surface in km. All logs are in Base 10.

f (Hz)	c_1	c_2	c_3	c_4
0.10	1.49	0.87338	-0.06085	-0.00185
0.13	1.66	0.83964	-0.05755	-0.00168
0.16	1.81	0.84255	-0.07228	-0.00156
0.20	1.98	0.82488	-0.07993	-0.00141
0.25	2.14	0.80463	-0.08661	-0.00127
0.32	2.31	0.77829	-0.09453	-0.00115
0.4	2.49	0.74685	-0.10534	-0.00111
0.5	2.66	0.70911	-0.11769	-0.00112
0.6	2.85	0.67139	-0.13161	-0.00114
0.8	3.03	0.62954	-0.14195	-0.00117
1.0	3.19	0.59407	-0.14813	-0.00122
1.3	3.37	0.55285	-0.15348	-0.00129
1.6	3.54	0.51563	-0.15932	-0.00141
2.0	3.69	0.47664	-0.15903	-0.00151
2.5	3.83	0.44721	-0.15754	-0.00161
3.2	3.95	0.41559	-0.15291	-0.00181
4.0	4.03	0.38958	-0.14469	-0.00201
5.0	4.10	0.35585	-0.13450	-0.00219
6.3	4.10	0.34067	-0.12530	-0.00235
8.0	3.96	0.33553	-0.11937	-0.00253
10.0	3.94	0.29497	-0.11064	-0.00259
12.5	3.89	0.28660	-0.10038	-0.00271
16.0	3.84	0.29420	-0.09576	-0.00272
PGA	3.67	0.33228	-0.11308	-0.00244
PGV	2.37	0.51396	-0.10160	-0.00184

**Figure 1. Comparison of Puerto Rico ground motion
realations with relations of other regions.
M7.0, f=1.0 Hz (NEHRP C)**

